Magnetic Field Sensor Based on Spin-Hall Nano-Oscillators

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Primary CNF Tools Used: JEOL 9500, SÜSS MA6 Contact Aligner

Abstract:

Spin-Hall nano-oscillators (SHNOs) are magnetic bilayer devices that convert DC charge current to microwave frequency magnetic oscillations under external magnetic field. The oscillation frequency of a SHNO is linearly dependent on the external magnetic field strength, and thus SHNOs can be used as bias magnetic field sensors. We demonstrate the ability of our SHNO sensor to sense small AC magnetic field with a detectivity of less than 1 $\mu T/\sqrt{Hz}$ for AC magnetic field frequency > 20-100 Hz, despite having small effective sensing area ranging from 0.32 µm^2 tp 0.071 µm^2.

Summary of Research:

The spin Hall effect (SHE) is the generation of transverse spin currents by electric currents. In a non-magnetic material (NM), this leads to the accumulation of spins with opposite polarization at opposite edges of the NM [1,2]. By placing a nonmagnetic film on top of a ferromagnetic film, the spin current generated in the NM can diffuse into the ferromagnet (FM), providing spin transfer torque (STT) to the FM [1]. Under suitable conditions, the STT is able to compensate the damping of magnetic precession, leading to steady precession of magnetization [3]. With this principle, spin-Hall nano-oscillators (SHNOs) are developed as a bilayer system consisting of NM and FM, patterned as nanowires or nanoconstrictions.

In our study we fabricated arrays of four $Ni_{81}Fe_{19}$ (5 nm)/ $Au_{0.25}Pt_{0.75}$ (5 nm) constriction-based SHNOs on 20.5 µm × 4 µm wires. Devices included both single w = 150 nm constriction and arrays of four w = 150 nm constrictions separated by a = 350 nm, with a lateral shift along -30° from the x axis, perpendicular to the magnetic field direction (Figure 1). This shifted design is to maximize the overlap between spin wave modes, as spin wave emission is perpendicular to magnetic field [4]. We used JEOL 9500 for the e-beam patterning of the SHNOs, and SÜSS MA6 contact aligner and evaporator for depositing contact pads for electrical measurements.

We use a home-built spectrum analyzer (Figure 1) to perform auto-oscillation measurements and sensing. The device is placed in an electromagnet which applies a magnetic field H = 400 Oe. A DC charge current I_{dc} is applied to the device to excite auto-oscillation. The output gigahertz signal is then amplified and down-convert to megahertz (MHz) frequency by mixing it with the output from a local oscillator (LO). The output MHz signal then goes through a preamplifier before being converted to voltage signal by a RF diode. This voltage signal then goes through another preamplifier and is finally converted to a digital signal.

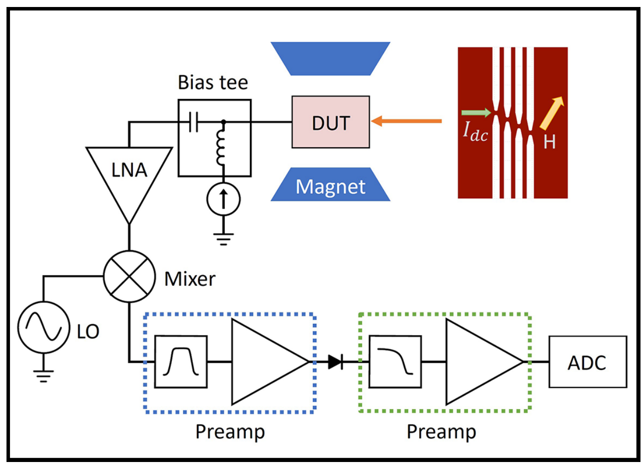

Figure 1: Schematic of measurement circuit and device under test.

As we scan the frequency of LO, when the frequency of LO matches the auto-oscillation frequency from SHNO device, a peak shows up. To operate the SHNO device as a sensor, we keep the frequency of LO at the steepest slope on the peak and monitor the output voltage. As

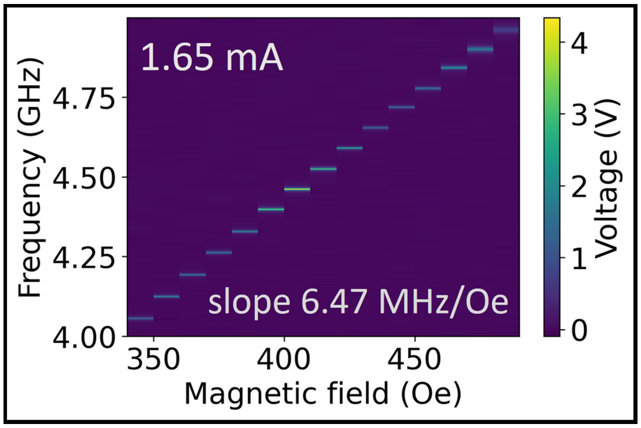

Figure 2: Auto-oscillation frequency dependence on external magnetic field under charge current I_{dc} = 1.65 mA.

the external magnetic field slightly deviates, the output voltage changes and thus we are able to measure the change in the external magnetic field.

Figure 2 shows the linear dependence of oscillation frequency on the array device under an external magnetic field at I_{dc} = 1.65 mA, with a slope df/dH = 6.47 × 10^{-3} GHz/Oe. Averaging 3000 scans over the same frequency range yields a linewidth of 6.4 MHz and a maximum dV/df = 312 V/GHz, corresponding to a sensor sensitivity $S = dV/dH$ = 2.02 V/Oe.

The detectivity of sensor is characterized by measuring the linear spectral density and dividing by the sensitivity at the optimal operating conditions. For this sensor, the detectivity goes below 1 $\mu T/\sqrt{Hz}$ for AC magnetic field frequency > 20 Hz, shown in Figure 3. The noise floor of our SHNO sensor is close to $1/\sqrt{f}$ line, indicating the noise in our sensor is dominated by the pink noise. Note that the effective sensing area is the constriction region, which is less than 0.32 μm².

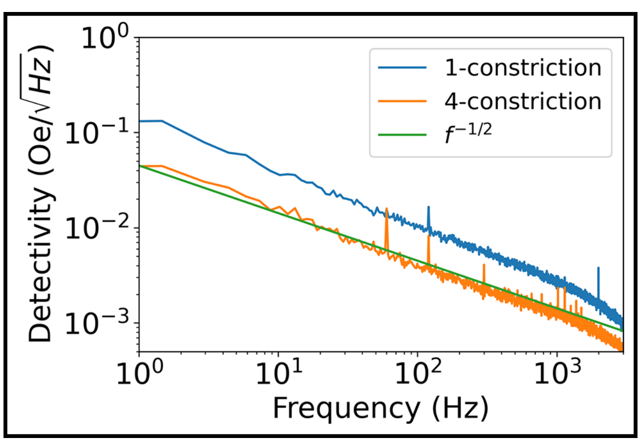

Figure 3: Noise floor of SHNO sensor at optimal operating conditions in comparison to $1/\sqrt{f}$ line.

We also fabricated a 1-constriction device with constriction width w = 150 nm for comparison. For the 1-constriction device, the detectivity goes below 1 $\mu T/\sqrt{Hz}$ for AC magnetic field frequency > 100 Hz (Figure 3), but the effective sensing area is reduced to 0.071 μm².

To demonstrate the ability to sense small magnetic variation, we place the 4-constriction array in an AC modulating field with a rms value of 0.153 Oe, and measure the output from the senor and from a Gaussmeter with its probe near the sensor. From Figure 4, the output from our sensor agrees well with the Gaussmeter.

Conclusions and Future Steps:

We developed a bias magnetic field sensor based on spin-Hall nano-oscillators to sense small variation in magnetic field within a nanoscale area, which has a detectivity of less than 1 $\mu T/\sqrt{Hz}$ for AC magnetic field frequency > 20 Hz. We have characterized quasi-DC sensing for up to kilohertz-scale frequencies. We plan to extend the measurement range up to MHz based on sideband modulation.

References:

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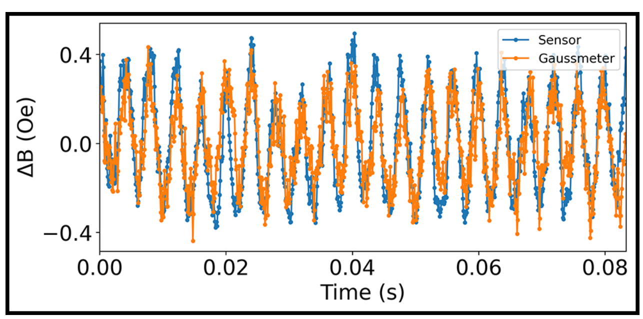

Figure 4: Comparison of measurements of a 251 Hz modulation field with a rms 0.153 Oe from the 4-constriction SHNO sensor and the Gaussmeter.